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Synthesizing Deuterium in Incipient Pop II Stars

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Abstract

Sites for incipient low metallicity (Pop II) star formation can support environments conducive to Deuterium production up to levels observed in the universe. This could have a deep impact on a "Standard Cosmology".

1 Introduction:

Early universe (standard big-bang) nucleosynthesis [SBBN] is regarded as a major success for the Standard Big Bang [SBB] Model. The results look rather good indeed. The observed light element abundances are taken to severely constrain cosmological and particle physics parameters. Deuterium, in particular, is regarded as an ideal "baryometer" for determining the baryon content of the universe [1]. This follows from the fact that deuterium is burned away whenever it is cycled through stars, and a belief, that there are no astrophysical cites (other than SBBN), capable of producing it in its observed abundance [2]. The purpose of this article is to admit caution in adhering to this belief.

What would be the point of such an exercise ?

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Indeed, at the outset, drastic variations from SBBN may sound preposterous at this time. Confidence in SBBN stems primarily from D, ^7Li and ^4He measurements. D abundance is measured in the solar wind, in interstellar clouds and, more recently, in the inter-galactic medium [3, 4]. The belief that no realistic astrophysical process other than the Big Bang can produce sufficient D, lends support to its primordial origin. Further, ^7Li measurement [$^7Li/H \sim 10^{-10}$] in Pop II stars [5] and the consensus [6] over the primordial value for the ^4He ratio $Y_p \geq 23.4\%$ (by mass) suggest that light element abundances are consistent with SBBN over nine orders of magnitude. This is achieved by adjusting just one parameter, the baryon entropy ratio η. Alternative mechanisms for ^7Li production that are accompanied by a co-production of ^6Li with a later depletion of ^7Li have fallen out of favour. The debate on depletion of ^7Li has been put to rest by the observation of ^6Li in a Pop II star [7]. Any depletion of ^7Li would have to be accompanied by a complete destruction of the much more fragile ^6Li. Within the SBBN scenario therefore, one seeks to account for the abundances of ^4He, D, ^3He and ^7Li cosmologically, while Be, B and ^6Li are generated by spallation processes [8].

These results, however, do meet with occasional skepticism. Observation of ^6Li, for example, requires unreasonable suppression of astrophysical destruction of ^7Li. On the other hand, the production of ^6Li would be accompanied by a simultaneous production of ^7Li comparable to observed levels [9]. This raises doubts about using observed ^7Li levels as a benchmark to evaluate SBBN.

Further the best value of ^4He mass fraction, statistically averaged and extrapolated to zero heavy element abundances, hovers around $.216 \pm .006$ for Pop II objects [10]. Such low ^4He levels have also been reported in several metal poor HII galaxies [11]. For example for SBS 0335-052 the reported value is $Y_p = 0.21 \pm 0.01$ [12]. Such small values for ^4He would not lead to any concordant value for η consistent with bounds on ^7Li and D. Of course, one could still explore a multi-parameter non-minimal SBBN instead of the minimal model that just uses η for a single parameter fit. Non-vanishing neutrino chemical potentials have been proposed to be "natural" parameters for such a venture. These conclusions have been criticized by [6, 12] who rely on statistical over-emphasis on a few metal-poor objects with a high enough ^4He abundance to save minimal SBBN. On the other hand, there are objects reported with abysmally low ^4He levels. This is alarming for

minimal SBBN. For example, levels of ^4He inferred for μ Cassiopeiae A [12] and from the emission lines of several quasars [13] are as low as 5% and 10 - 15% respectively. Such low levels would most definitely rule out SBBN. At present one excludes such objects from SBBN considerations on grounds of "our lack of understanding"of the environments local to these objects. As a matter of fact, one has to resort to specially contrived explanations to account for low Y_p values in quasars. Considering that a host of mechanisms for light element synthesis are discarded on grounds of requirement of special "unnatural" circumstances [2], it does not augur to have to resort to special explanations to contend with low ^4He emission spectra. This comment ought to be considered in the light of much emphasis that is laid on emission lines from nebulae with low metal content [6]. Quasars most certainly qualify for such candidates. Instead, one merely seems to concentrate on classes of Pop II objects and HII galaxies that would oblige SBBN. Until the dependence of light element abundance on sample and statistics is gotten rid of and / or fully understood, one must not close one's eyes to alternatives.

We end our overview of the status of SBBN with a few comments. Firstly the low metallicity that one sees in type II stars and interstellar clouds poses a problem in SBBN. There is no object in the universe that has quite the abundance [metallicity] of heavier elements as is produced in SBB. One relies on some kind of re-processing, much later in the history of the universe, to get the low observed metallicity in, for example, old clusters and interstellar clouds. This could be in the form of a generation of very short-lived type III stars. Such a generation of stars may also be necessary to ionize the intergalactic medium. The extrapolation of ^4He abundance in type II objects and low metal (HII) galaxies, to its zero heavy metal abundance limit, presupposes that reprocessing and production of heavy elements in type III stars is not accompanied by a significant change in the ^4He levels. A violation of this assumption, i.e. a minute increase in ^4He during reprocessing (even as low as 1 - 2 %) would rule out the minimal SBBN. As a matter of fact, it is possible to account for the entire pre-galactic ^4He by such objects [14].

Finally, of late [15], the need for a careful scrutiny and a possible revision of the status of SBBN has also been suggested from the reported high abundance of D in several Ly_α systems. It may be difficult to accommodate such high abundances within the minimal SBBN. Though the status of these observations is still a matter of debate, and (assuming their confirmation) attempts to reconcile the cosmological abundance of deuterium and the

number of neutrino generations within the framework of SBB are still on, a reconsideration of alternate routes to deuterium presented below could well be worth the effort. This is specially in consideration of the stranglehold that Deuterium has on SBB in constraining the baryon density upper limit to not more than some 3 to 4 % . This constraint has been used in SBB to make out a strong case for non - baryonic dark matter to make up the mass estimates at galactic and cluster scales. Relying on Deuterium that is so local environment sensitive, to predict the nature of CDM runs the risk of "building a colossus on a few feet of clay"[16]

Deuterium Production:

To get the observed abundances of light elements besides ^4He, we recall spallation mechanisms that were explored in the pre - 1976 days [2]. Deuterium can indeed be produced by the following spallation reactions:

$$p +^4 He \longrightarrow D +^3 He; \;\; 2p \longrightarrow D + \pi^+;$$

$$2p \longrightarrow 2p + \pi^o, \; \pi^o \longrightarrow 2\gamma, \; \gamma +^4 He \longrightarrow 2D.$$

There is no problem in producing Deuterium all the way to observed levels. The trouble is that under most conditions there is a concomitant over - production of Li nuclei and γ rays at unacceptable levels. Any later destruction of lithium in turn completely destroys D. As described in [2], figure (1) exhibits relative production of ^7Li and D by spallation. It is apparent that the production of these nuclei to observed levels and without a collateral gamma ray flux is possible only if the incident (cosmic ray or any other) beam is energized to an almost mono energetic value of around 600 MeV. A model that requires nearly mono energetic particles would be rightly considered *ad hoc* and would be hard to physically justify.

However, lithium production occurs by spallation of protons over heavy nuclei as well as spallation of helium over helium:

$$p, \alpha \; + \; C, N, O \longrightarrow Li \; + \; X; \;\; p, \alpha \; + \; Mg, Si, Fe \longrightarrow Li \; + \; X;$$

$$2\alpha \longrightarrow^7 Li \; + \; p; \;\; \alpha \; + \; D \longrightarrow p \; + \; ^6Li;$$

$$^7Be + \gamma \longrightarrow p +^6 Li; \;\; ^9Be + p \longrightarrow \alpha +^6 Li.$$

The absence or deficiency of heavy nuclei in a target cloud and deficiency of alpha particles in the incident beam would clearly suppress lithium production. Such conditions could well be imagined in the environments of incipient Pop II stars.

Essential aspects of evolution of a collapsing cloud to form a low mass Pop II star is believed to be fairly well understood [17, 18]. The formation and early evolution of such stars can be discussed in terms of gravitational and hydrodynamical processes. A protostar would emerge from the collapse of a molecular cloud core and would be surrounded by high angular momentum material forming a circumstellar accretion disk with bipolar outflows. Such a star contracts slowly while the magnetic fields play a very important role in regulating collapse of the accretion disk and transferring the disk orbital angular motion to collimated outflows. A substantial fraction of the accreting matter is ejected out to contribute to the inter - stellar medium.

Empirical studies of star forming regions over the last twenty years have now provided direct and ample evidence for MeV particle produced within protostellar and T Tauri systems [19, 20]. The source of such accelerated particle beaming is understood to be violent magnetohydrodynamic (MHD) reconnection events. These are analogous to solar magnetic flaring but elevated by factors of 10^1 to 10^6 above levels seen on the contemporary sun besides being up to some 100 times more frequent. Accounting for characteristics in the meteoritic record of solar nebula from integrated effects of particle irradiation of the incipient sun's flaring has assumed the status of an industry. Protons are the primary component of particles beaming out from the sun in gradual flares while ^4He are suppressed by factors of ten in rapid flares to factors of a hundred in gradual flares[19, 20]. Models of young sun visualizes it as a much larger protostar with a cooler surface temperature and with a very highly elevated level of magnetic activity in comparison to the contemporary sun. It is reasonable to suppose that magnetic reconnection events would lead to abundant release of MeV nuclei and strong shocks that propagate into the circumstellar matter. Considerable evidence for such processes in the early solar nebula has been found in the meteoric record. It would be fair to say that the hydrodynamical paradigms for understanding the earliest stages of stellar evolution is still not complete. However, it seems reasonable to conjecture that several features of collapse of a central core and its subsequent growth from acreting material would hold for low metallicity Pop II stars. Strong magnetic fields may well provide for a link between a central star, its circumstellar envelope and the acreting disk. Acceleration of jets of charged particles from the surface of such stars could well have suppressed levels of ^4He. Such a suppression could be naturally expected if the particles are picked up from an environment cool enough to suppress

ionized ^4He in comparison to ionized hydrogen. Ionized helium to hydrogen number ratio in a cool sunspot temperature of $\approx 3000\ K$ can be calculated by the Saha's ionization formula and the ionization energies of helium and hydrogen. This turns out to be $\approx\ exp(-40)$ and increases rapidly with temperature. Any electrodynamic process that accelerates charged particles from such a cool environment would yield a beam deficient in alpha particles. With ^4He content in an accelerated particle beam suppressed in the incident beam and with the incipient cloud forming a Pop II star having low metallicity in the target, the "no - go" concern of (Epstein et.al. [2]) is effectively circumvented. The "no-go" used $Y_\alpha/Y_p \approx .07$ in both the energetic particle flux as well as the ambient medium besides the canonical solar heavy element mass fraction. Incipient Pop II environments may typically have heavy element fraction suppressed by more than five orders of magnitude while, as described above, magnetic field acceleration could accelerate beams of particles deficient in ^4He.

One can thus have a broad energy band - all the way from a few MeV up to some 500 MeV per nucleon as described in the Figure 1, in which acceptable levels of deuterium could be "naturally" produced. The higher energy end of the band may also not be an impediment. There are several astrophysical processes associated with gamma ray bursts that could produce D at high beam energies with the surplus gamma ray flux a natural by product.

Conclusions:

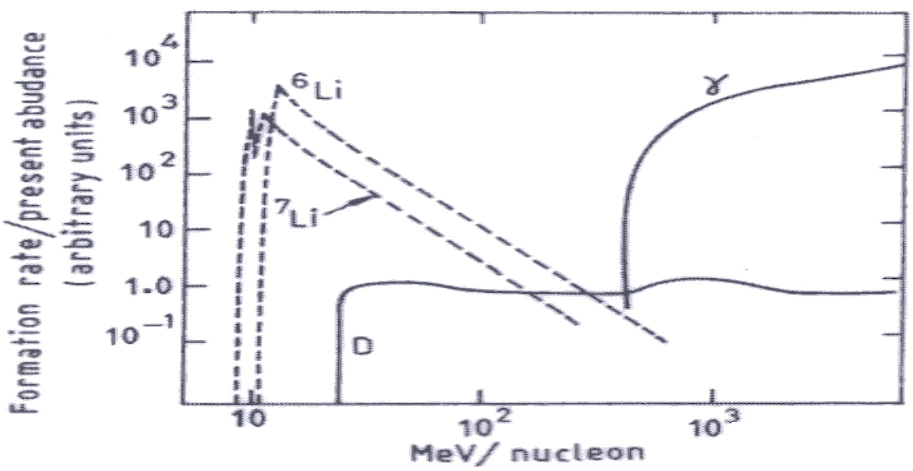
Our understanding of star formation has considerably evolved since 1976. SBBN constraints need to be reconsidered in view of empirical evidence from young star forming regions. These models clearly imply that spallation mechanism can lead to viable and natural production of Deuterium and Lithium in the incipient environment of Pop II stars. One can conceive of a cosmological model in which early universe nucleosynthesis produces the desired primordial levels of ^4He but virtually no D. Such a situation can arise in SBBN itself with a high baryon entropy ratio η. In such a universe, in principle, Deuterium and Lithium can be synthesized up to acceptable levels in the environment of incipient Pop II stars.

In SBB, hardly any metallicity is produced in the very early universe. Metal enrichment is supposed to be facilitated by a generation of Pop III stars. Pop III star formation from a pristine material is not well understood till date in spite of a lot of effort that has been expanded to that effect in the recent past [21]. It is believed that with metallicity below a critical

transition metallicity ($Z_{cr} \approx 10^{-4} Z_{\odot}$), masses of Pop III stars would be biased towards very high masses. Metal content higher than Z_{cr} facilitates cooling and a formation of lower mass Pop II stars. In SBB, the route to Deuterium by spallation discussed in this article would have to follow a low metal contamination by a generation of Pop III stars.

Deuterium production by spallation discussed in this article would be good news for a host of slowly evolving cosmological models [22, 23]. An FRW model with a linearly evolving scale factor enjoys concordance with constraints on age of the universe and with the Hubble data on SNe1A. Such a linear coasting is consistent with the right amount of helium observed in the universe and metallicity yields close to the lowest observed metallicities. The only problem that one has to contend with is the significantly low yields of deuterium in such a cosmology. In such a model, the first generation of stars would be the low mass Pop II stars and the above analysis would facilitate the desired deuterium yields.

In SBB, large-scale production and recycling of metals through exploding early generation Pop III stars leads to verifiable observational constraints. Such stars would be visible as 27 - 29 magnitude stars appearing any time in every square arc-minute of the sky. Serious doubts have been expressed on the existence and detection of such signals [24]. The linear coasting cosmology would do away with the requirement of such Pop III stars altogether.



Formation rate/present abudance
(arbitrary units)
10^4
10^3
10^2
10
1.0
10^{-1}
^{6}Li
^{7}Li
γ
D
10
10^2
10^3
MeV/ nucleon

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